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Guided-Wave Testing of Trunnion Rods at Greenup Lock and Dam, Kentucky

by James A. Evans and Rick Haskins

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the initial results of a field test at Greenup Lock and Dam, Kentucky (Figure 1), to evaluate the existing laboratory equipment and the methodology of acoustical guided waves to determine the field condition of trunnion rods used in US Army Corps of Engineers (USACE) dams throughout the country. This effort is funded by the Navigation Research Program at the Engineering Research and Development Center (ERDC).

Figure 1. Greenup Lock and Dam

INTRODUCTION: Post-tension trunnion anchor rods are a critical structural element in a large number of USACE tainter gates (Figure 2). A significant number of these rods have failed, and it is not known how many rods are currently in a defective, pre-failure state. It is also not known whether the present failure rate will increase significantly in the future (Figure 3).

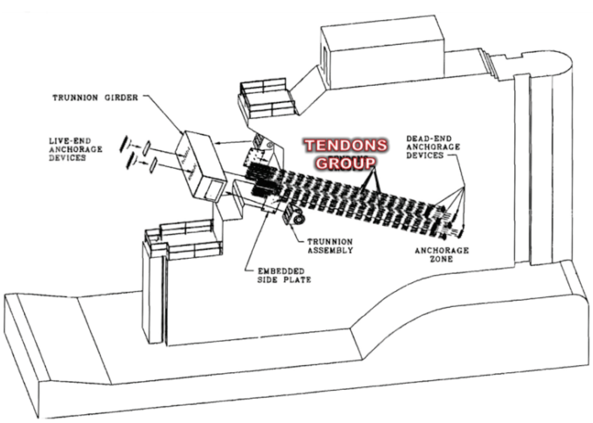

Figure 2. Typical dam pier with trunnion rods shown.

Figure 3. Broken Trunnion Rods at RF

Unlike fatigue cracks which go through opening and closing periods during their progression, microcracks in post-tension trunnion anchor rods are believed to be closed in their initial phase and to open up as the crack area increases. The presence of soft corrosion product in the crack area is

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evidence for this open-crack assumption. When a rod's crack reaches a critical area and crack intensity factor, it then fails in a brittle manner. This migration of a crack from a closed state to an open state correlates to a change in acoustic detection from nonlinear methods to linear methods.

BACKGROUND: Initial investigations in this research effort established proof of concept for remote closed-crack detection using nonlinear methods. In the second stage of this research effort, linear guided-wave methods have been developed and evaluated to obtain end-of-rod reflections for the high rate of attenuation present in full-length grease- and grout-surrounded rods.

Rick Haskins and Ken Switzer performed tests at Greenup Lock and Dam during the week of 26 March 2013. These tests were performed in support of the Navigation Program Trunnion Rod research program at ERDC Vicksburg, MS. The Greenup Lock and Dam inspection served to evaluate the field performance of acoustical guided-wave test methods on in situ rods. Additional background information relating to these rods and the initial ERDC research efforts aimed at development of a non-destructive method of inspection are provided in the following Technical Note: ERDC/CHL CHETN-IX-32 (Evans 2012).

Test-bed-based investigations have also addressed influences from tension, end conditions, and methods for frequency and mode determination (findings to be published in an upcoming technote). Laboratory experimentation confirmed that the current system is capable of detecting a 0.1 in. deep open crack in a 1.3 in. diameter embedded rod at a distance exceeding 50 ft. The next stage of this research will integrate these techniques to produce a system capable of detecting microcracks in trunnion anchor rods throughout their evolution. The higher-order, ultrasonic guided-wave inspection testing approach being developed at the ERDC test bed proved successful for inspection of the highly attenuating trunnion anchor rods at Greenup Lock and Dam. Initial on-site frequency scans were used to determine the specific low-attenuation, narrow-band, guided-wave propagation modes best suited for pulse-reflection measurements and their variability.

At Greenup Lock and Dam, the small diameter (1.125 in.) and longer length (80 ft) rods make the end-of-rod echo detection case here a worst-case scenario. Findings from the Greenup Lock and Dam testing, along with laboratory measurements, have been used to design and develop an improved system which will enhance the effective dynamic range of the digitizing hardware, enable further reduction of non-stationary noise, and optimize echo detection along the entire length of the rod. The dynamic range improvement from this modified system will aid in the implementation of guided-wave-based, nonlinear methods such as gated frequency mixing, harmonic analysis, and impact modulation for closed-crack detection.

TENSION TESTING PERFORMED BY A PRIVATE NDT COMPANY: A 2012 followup flexural vibration-based test, which used pull-off mechanical load testing and empirical computer modeling to develop correlations between measured-rod, low-frequency flexural vibrations and a rod-tension state, was also recently performed at Greenup Lock and Dam by a private non destructive testing (NDT) company (Cesare et al. 2013). Results of the second investigation have just been published at the time of this writing. The first tension analysis relied on a number of assumptions due to the lack of pull-off data for correlation. The second analysis compared empirical modeling and load test results to explore the possibility of 3D finite element modeling (FEM) as a means to avoid pull-off requirements. It is important to note that this low-frequency, vibration-based approach is not expected to be sensitive to the presence of a closed or open

microcrack for the following reasons: (1) an open crack will not produce a detectable change in rod tension given the modulus of steel and realistic size crack openings and (2) while a crack would affect the low-load-dominant, cantilever-vibration mode where the restoring force is a function of the material properties and geometry, a crack will not significantly change the taught-string vibration mode which is dominant at trunnion-anchor operational loads. Preliminary results from this effort indicate that cantilever length, material modulus, and grip nut contact can have significant influence on the dominant measured frequencies when compared to the influence due to tension.

GUIDED WAVE TENSION INFLUENCE: Using modulus relations with estimated entities of diameter and length, it is estimated approximately 0.3 in. of rod stretch per 10,000 lb variation in load. This would indicate that at a sample rate of 100 MHz, a shift in pulse arrival time of approximately 250 samples (or 2.4 microseconds) would result as the roughly 19,000 ft/sec pulse traveled through the stretched length twice (incident and reflected). This indicates a potential high level of differentiation in detected changes in rod length caused by changes in tension.

Also considered were diameter changes relating to tension which would be promising as the diameter influence on guided waves is clearly observed in the frequency spacing of low attenuation modes. Poison's ratio indicates that the diameter will only change by approximately .0013 in. over the rod's elastic range which is too small to discern in mode spacing in the frequency domain. The observed echo shifting due to length changes at Greenup Lock and Dam was larger by at least a factor of two than what could be explained due to nominal tension variations. It is likely that there is additive influence from variations in delivered rod lengths. The ERDC guided-wave method appears to be extremely sensitive to *changes* in tension due to the short wavelength and high sample rate being used. A method of intersecting guided wave modes was developed in the test bed that provides a robust, simple, and repeatable method of time-of-arrival estimation on a given rod. This method is also well-suited to real-time monitoring methods using active acoustics. An example is given at the end of the following section as well as results from tension-based, guided-wave investigations performed in the ERDC test bed.

Pre-Greenup Lock and Dam ERDC Test-bed investigations. A failed small diameter rod of approximately the same diameter (1.25 in.) as the Greenup Lock and Dam rods was recovered from a vertical miter-gate post-tensioning pier. This rod proved valuable in pre- and post-Greenup Lock and Dam investigations as well as general investigation on the influence of diameter variations. This section of the report covers group velocity, attenuation, and tension investigations performed at the ERDC test bed in preparation for Greenup Lock and Dam field testing.

Using a grease-encased laboratory rod of similar diameter at the ERDC test bed, the group velocity at the lowest-loss inspection frequency was estimated. The Greenup Lock and Dam rods were on average 1.1425 in. in diameter, and the ERDC post-tension rod was slightly larger at 1.16 in. It should be noted that the cold-rolled, post-tension rods, whether large or small, are not perfectly round, and the diameter appears to vary by 1 to 3 percent. The laboratory rod was used to develop an understanding of the group velocity at the target inspection frequency.

Guided-wave inspection using narrowband pulse energy consists of two velocity properties for a given frequency and mode of propagation. These are the phase velocity, which is the speed of the

high-frequency transmitted energy traveling along the test object, and the slower group velocity, which is the slowly changing envelope of the transmitted pulse. The group velocity can be thought of as the actual information signal, and the entity which, during pulse-echo measurements, is used to describe the time of arrival and, therefore, to determine the distance to various reflectors. In bulk material testing, these two entities are the same; however, in acoustical waveguides, they generally are not the same (the exception is the fundamental torsional wave mode). The group velocity is slower than the bulk material velocity because it is developed from multiple reflections and refractions from the waveguide surface. In movement from lower to higher frequencies of low-loss propagating modes, the group velocity of mode peaks generally increases. For the optimum low-loss modes in the larger 1.25 in. and smaller 1.125 in. (design specs) test-bed rod (Table 1), the group velocity is approximately 18,691 ft/sec and 19,000 ft/sec, respectively. This estimated 19,000 ft/sec group velocity, based on laboratory measurements, was used to estimate a typical Greenup Lock and Dam rod length of approximately 81.7 ft. This measurement was in agreement with Greenup Lock and Dam blueprint drawings.

Table 1. Low attenuation modes for various rod diameters.

Average	Optimum
Rod Diameter (inch)	**Frequency (Mhz)**
1.1425	1.986
1.159	1.957
1.3125	2.175

Attenuation studies on the small diameter test bed rod were also performed prior to the Greenup Lock and Dam inspection. In general, the grease and grout surrounding in situ, post-tension anchor rods will *drain* the ultrasonic inspection energy from rod. For vertical and horizontal (or torsional) shear wave energy, this effect is worsened by their higher intrinsic material attenuation. For the higher order (higher frequency) longitudinal modes in the L(0,9) to L(0,12) range, the ultrasonic energy becomes more centralized in the rod, and very narrow bands of frequencies can be found where there are minimal surface displacements. This lower surface displacement results in relatively much lower attenuation rates (Pavlakovic 2001). Laboratory testing has validated that these low-surface energy modes are still capable of detecting very shallow defects at great distances downrange. These tuned modes also avoid the issue of coupling energy into and out of the steel pipe sleeve containing the rod which would otherwise generate false backwall echoes. Additionally, the bulkheads and sleeve contacts do not tend to significantly drain or reflect these higher order modes either. As the frequency continues to increase, the intrinsic ultrasonic material attenuation also increases. This creates a point of diminishing return or an optimum inspection point between the improvement in energy centralization as frequency is increased, and the reduction in material attenuation as frequency is reduced.

Using relative amplitudes of first, second, and third reflections, a grease-embedded attenuation rate was estimated for the various rod diameters. For the smaller Greenup Lock and Dam rods, an attenuation rate as high as 0.6 db/ft per propagated length was measured. This means the amplitude of the reflected signal is halved for every 2.5 ft of rod length (2.5 ft (rod length) × 2 (two-way dist) × 0.6 (db/ft) = 3 db). This estimate did not incorporate the small end losses which occur due to

mode conversion when the signal reflects off the end of the rods. The larger diameter 1.31 in. rods exhibited significantly less attenuation at their low-loss mode, with attenuation rates being approximately 0.2 (db/ft). For a 0.125 in. reduction in rod diameter from the more common 1.25 inch rods, the attenuation rate is tripled. These high attenuation rates challenges are being compensated for with customized amplification circuits discussed in a latter section of this report. The Greenup Lock and Dam rods exhibited approximately 96 db of attenuation for the roughly 160 ft of signal propagation.

Test-bed investigations were performed to evaluate the influence of tension on the inspection frequency and high-frequency, guided-wave propagation modes. As the rod length increases due to tension and the modulus of elasticity, the wave also propagates a longer distance. This relation for the rod is described by its modulus (31.6×10^6) which is equal to stress over strain, where strain is the change in length over initial length, and stress is the force per unit area. The specified area is 1.25 sq in. for the tensioned rod; however, the rod is more typically 1.31 in. in diameter which gives it an area of 1.347 sq in. Aside from making the rod longer and proportionally delaying the backwall echo, no other significant influence was determined. The spectral scans showed no detectable frequency change across a broad range of applied tensions. There are both positive and negative aspects of this. On the positive side, the selected inspection frequency is robust and will not change significantly as load variations fluctuate. On the negative side, this spectral amplitude information is not likely to be a useful mechanism for indication of applied load. Figure 4.a shows the pulse delay from varying load on the dominant inspection frequency as the load is increased to 140,000 pounds. Figure 4.b shows the intercept of three sequential, low-loss frequency modes across the same variations in load. Note that this intercept provides a consistent marker for tracking the changes in load in a real-time-monitoring scenario. Also note in 4.b that the lower-frequency modes arrive significantly more slowly (red pulses), and the higher frequencies (blue pulse) arrive sooner.

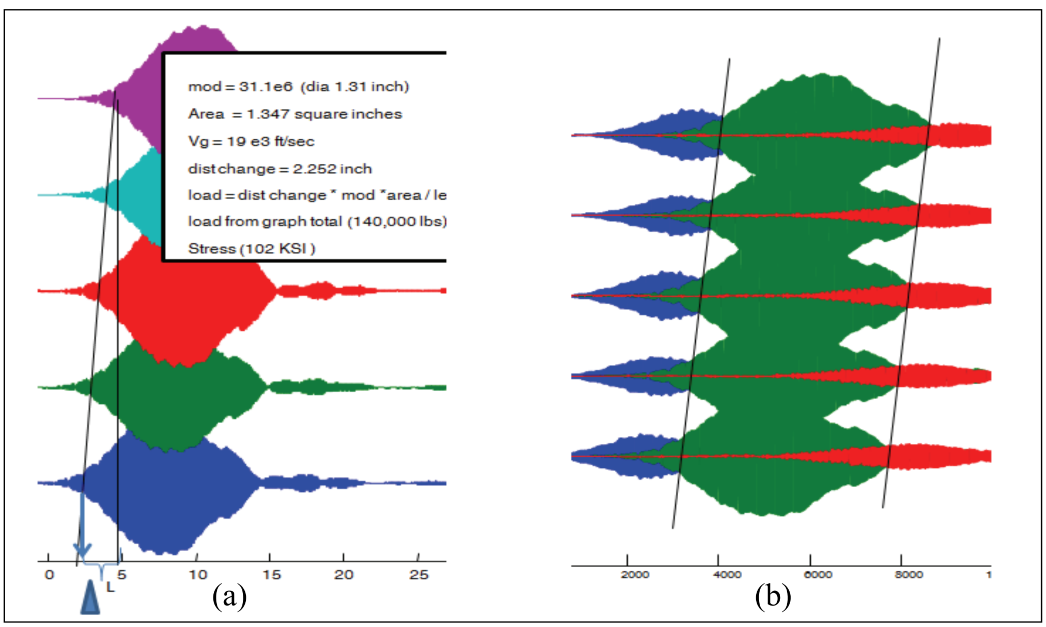

Figure 4. Variation in load and the resulting influence on propagation delay.

Guided-wave Testing at Greenup Lock and Dam. Because of the height and narrowness of the ladders, it was deemed impractical to transport the laboratory electronics down to the location of the trunnion anchor rods. Figure 5 shows the relative locations of the transducers and electronics. A small preamplifier was used to offset the influence of the return signal path.

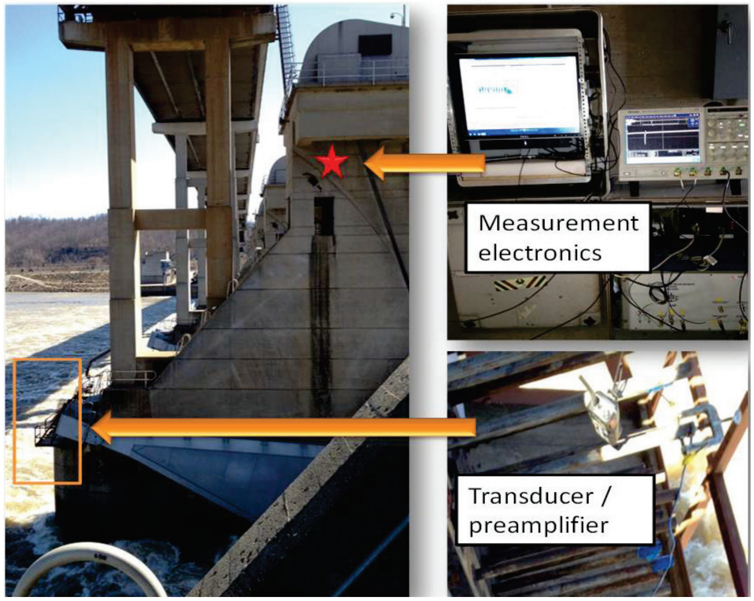

Figure 5. Location of testing equipment at Greenup Lock and Dam.

Prior to narrowband testing, numerous frequency scans were performed on randomly selected rods in each bank to determine the ideal guided-wave inspection parameters and to verify their consistency from rod to rod. Three of these frequency scans are shown in Figure 6. For the majority of tested rods, the backwall echo was obtained using 200 cycles of 1.9865 MHz ultrasonic energy. These parameters specify a lowest-loss, high-order longitudinal guided-wave mode for echo detection for the Greenup Lock and Dam rod and system configuration used. For a bank of rods which performed poorly to this frequency, additional testing was performed at a slightly higher center frequency (1.995 Mhz).

While the rod ends at Greenup Lock and Dam were factory-cut and nearly flat, there was a consistent high-edge artifact present from the factory finishing process. This small edge prevented ideal flat placement of the 1 in. diameter transducer. This small edge was easily and quickly removed with a flapper-type rotational sander. The very long and highly attenuating (small diameter) rods at Greenup Lock and Dam demonstrated the need for dynamic range enhancement of the system. In other words, to properly digitize the weak and attenuated backwall reflection, a large amount of signal gain (78 db at Greenup Lock and Dam) had to be applied which had the net effect of over-amplifying the ultrasonic backscattered energy in the front end of the signal. This saturation of the initial signal information is shown in Figure 7. To minimize the loss of echo information of the received signals where clipped well after the backwall echo with the goal that any near transducer reflections from cracks could be picked up in the reflection as the signal propagated back down the rod for the second time (i.e., to the right of the first end of rod reflection). The over saturation section is clipped in the remaining Greenup Lock and Dam data presentation. An improved solution to these problems is covered in the next section.

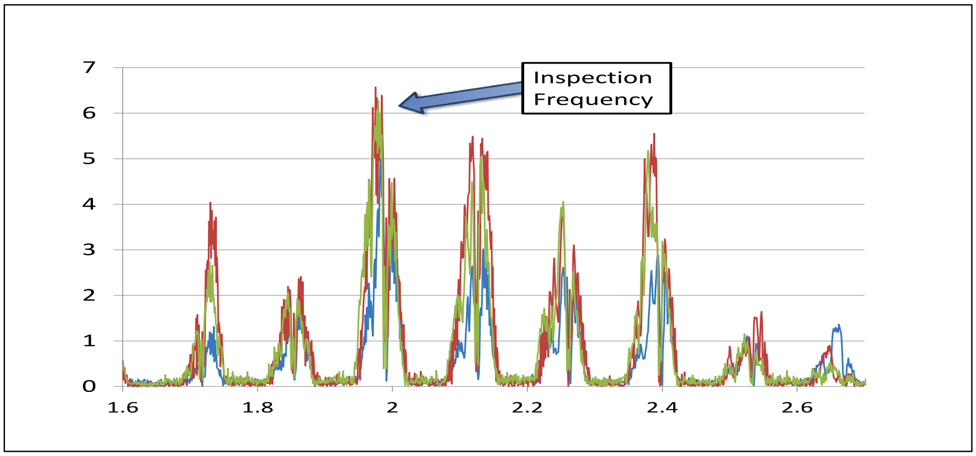

Figure 6. Three frequency scans at Greenup Lock and Dam and the selected low-loss inspection mode.

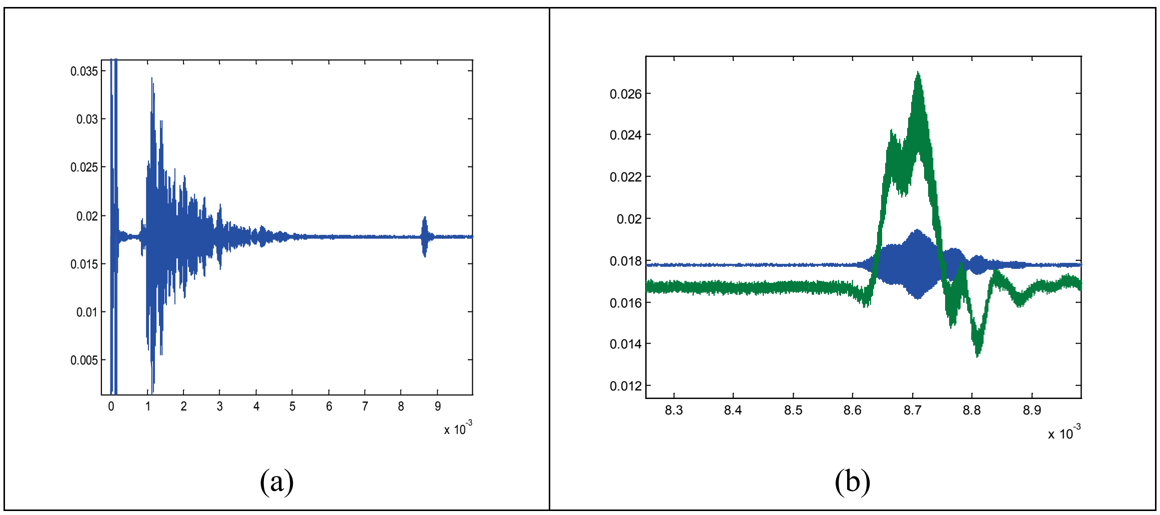

Figure 7. Typical signals showing front-end information loss due to high gain required for echo detection (right is zoomed in with overlaid receiver's phase-detected signal – green trace and radio frequency (RF) pulse shown in blue).

In addition to the RF signal shown in Figure 7, a heterodyne phase-detected signal was also digitized from the RITEC's output. This data is effectively a narrowband signal filtered to the transmitted frequency and amplitude-demodulated with respect to phase. This circuit can be very useful for improving the signal-to-noise ratio and stripping away the high-frequency carrier (or characterizing the envelope of the reflected energy). Figure 7b shows the reflected backwall pulse in both RF- and phase-detected forms. Note that the RITEC's analog phase detector will also be useful in future nonlinear acoustical experiments as it can detect and characterize (via integration) various harmonics and signal mixing (from its two independent pulsers). Figure 8 shows various representations of some of the signals collected at Greenup Lock and Dam. The center image in Figure 8 shows zoomed-in, phase-detected signals from the east-most pier. The circled region in the center panel shows rods that had weak backwall reflections and were rescanned and retested with a slightly higher inspection frequency. The figure on the right in Figure 8 shows the retested data zoomed in to the backwall.

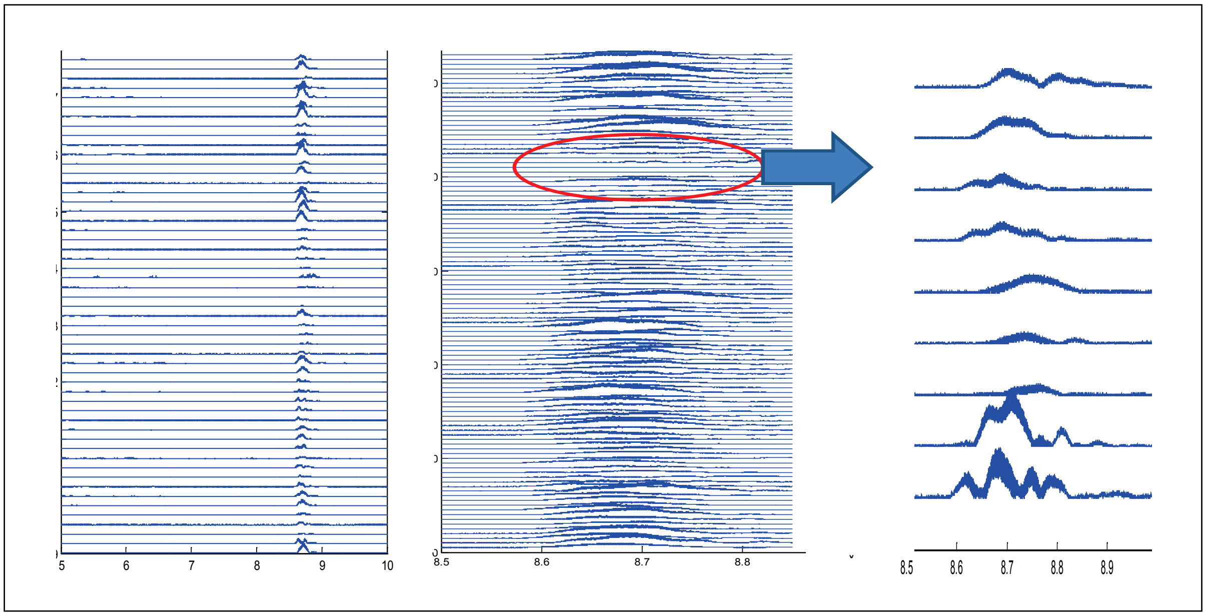

Figure 8. Various representations of some of the Greenup Lock and Dam test data. The X-axis is time in milliseconds (msec).

The shift in ideal inspection frequency seen in the lower section of the far-east bank of rods corresponded to a migration of the dominant peak from the left to the right of the null point in the low-loss frequency mode. This null point consistently appears in low-loss propagation modes and has been commented on by other guided-wave researchers (Beard 2003). Figure 9 shows this low-loss mode frequency migration in the spectral domain. The solid lines correspond to rods where the ideal inspection frequency shifted to the right of the null point. The new low-loss mode for this small subset of rods is approximately 1.995 Mhz. This change observed in this small group of rods is suspected to be due to either material property variations or curvature in the rod axis due to sleeve contact. Research (Beard 2003) indicates that cuvature as small as 800 times the rod diameter can be detected in guided-wave responses.

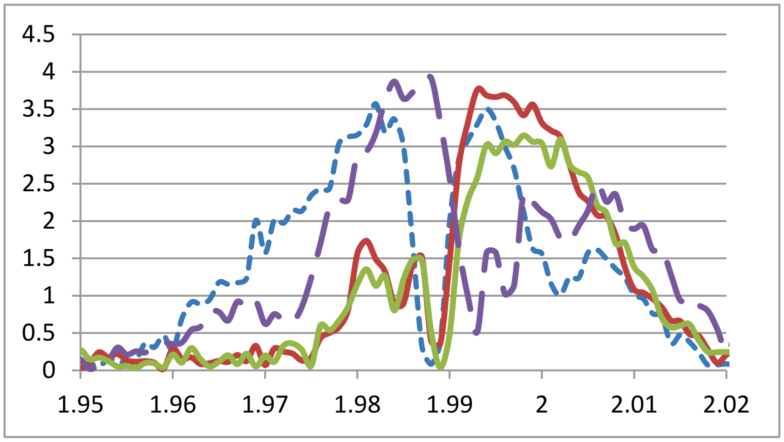

Figure 9. Shift in ideal inspection frequency as observed for a group of rods (pier 2, east bank).

Post Greenup Lock and Dam System Optimization. Three primary system improvements were determined and implemented following Greenup Lock and Dam testing. These improvements included a preamplifier, a time-compensated gain circuit, and a more powerful transducer.

Part of the initial signal loss observed at Greenup Lock and Dam had to do with the slow saturation recovery of the Olympus, Inc., preamplifier after the initial high-power pulse was transmitted. A high-pass filter was used to minimize this effect prior to digitization. Some of this saturation effect can be seen in Figure 7.a in the flat section of the signal before the 1 microsecond (µsec) mark. A RITEC amplifier was used in test-bed evaluations and was seen to exhibit 100 times faster settling time and, therefore, allowed recovery of this initial section of the signal. The improved recovery corresponded to 33 µsec settling time instead of the 3000 µsec seen with the Olympus preamplifier. Because the RITEC amplifier has inferior noise characteristics and is not battery powered, a new ultra-low-noise preamplifier with even faster recovery than the RITEC amplifier is being incorporated into the latest system design.

New transducers arrived shortly after the Greenup Lock and Dam field test and were evaluated on the small-diameter laboratory rod. The transducer used at Greenup Lock and Dam was a low-hat, dual-element design which has very low damping. This low damping is advantageous because it results in more detection sensitivity as well as ultrasonic power output. However, the low damping and quarter-wave matching layer were observed during impulse stimulation to produce several undesirable in-transducer reverberations every 6 µsec as the pulse bounced between the steel test surface and peizoceramic transducer. During guided-wave, tone-burst measurements, these reverberations produce undesired interference effects. A new 1.5 in. diameter, medium-damped lead zirconate titanate (PZT), ceramic-based crystal (i.e., an Accuscan model by Olympus) was seen to produce even better results without the interfering in-transducer reverberations. Because this transducer is more broadband than the dual-element design, it also allows a slightly wider window of candidate low-loss inspection modes. Figure 10 shows the improved signal levels from multiple reverberations of the 19 ft × 1.125 in. greased rod at ERDC. The circled echoes in Figure 10 correspond to the propagation length of the Greenup Lock and Dam rods. These signals have been amplified with the TCG circuit discussed next.

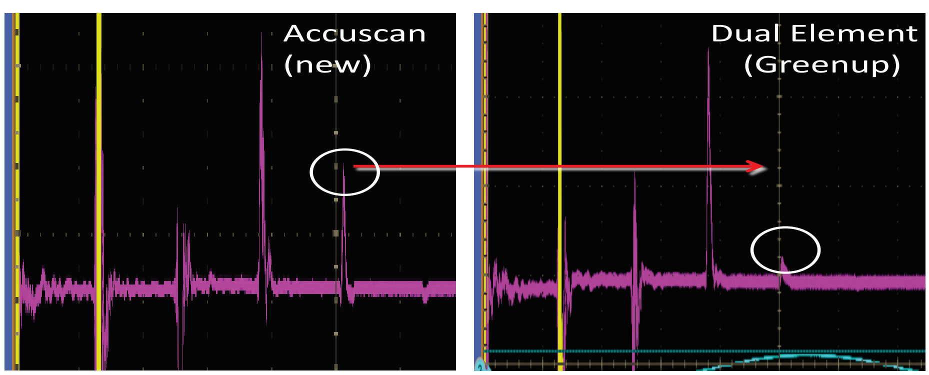

Figure 10. Improvement from Accuscan transducer over dual-element used at Greenup Lock and Dam.

Ultimately, several solutions to the dynamic range problem are possible, including signal integration across either various gains or pulser-output levels. The most elegant and common approach (used in radar and other range-dependent attenuation systems) is to use a time corrected

gain (TCG) circuit which allows the operator to dial in a gain function that increases with time (propagation time). The ideal gain function was seen to be a sine wave which starts at negative 90 degrees phase and ends at positive 90 degrees phase at the last detectable end-of-rod or backwall echo. This circuit adds some complexity to the system as it must be triggered in synch with the pulser and provided with an appropriate gain function. Currently, a 12-bit waveform generator is being used to apply the signal gain function. To date, three TCG integrated circuits have been evaluated, and another is on order. The best performers have allowed for negative gain (i.e., attenuation) of the front portion of the signal and had a wide gain function (60 db). Tests on near-transducer rods cuts were also evaluated to make sure that detectability in this range was not hampered. The TCG performed well in these evaluations. Using measurements on the 19 ft Greenup Lock and Dam representative rod, Figure 11 shows the front-end saturation as seen during field testing (top signal) and the improved signal after applying the TCG amplification (bottom signal).

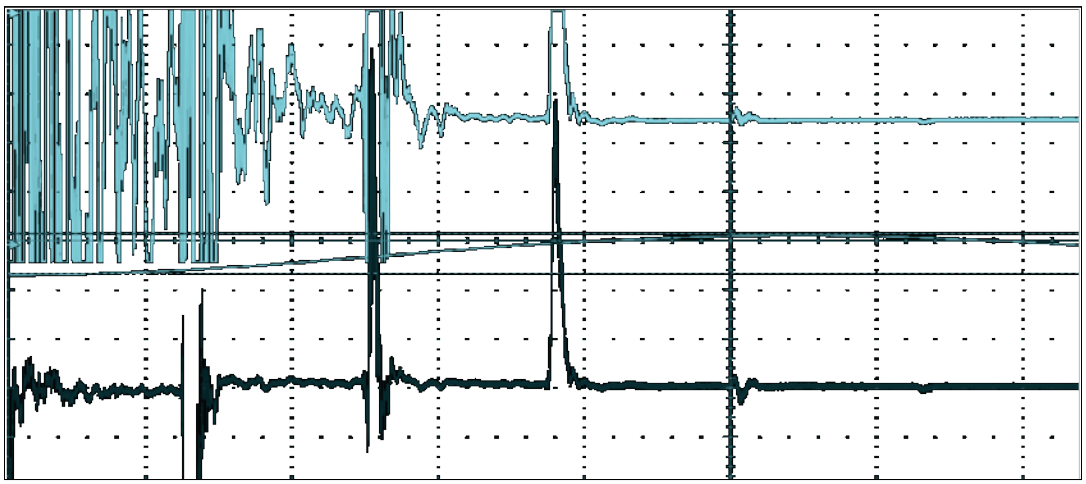

Figure11. Top signal shows Greenup Lock and Dam setting and front-end saturation for the representative small laboratory rod; the bottom signal shows the improvement after TCG application.

After inclusion of the TCG circuit, various system configurations were explored to determine the optimal configuration and settings of the various components. It was determined that the TCG circuit performed better with some degree of preamplification and that the TCG circuit produced the best results when applied before the RITEC's phase detector. The final optimized circuit is shown in Figure 12. As noted earlier, common triggering between the function or waveform generator, the TCG circuit, RITEC system, and oscilloscope is required. Efforts are underway to integrate the function generator, TCG, and preamplifier circuits into one unit with simplified controls for field setup.

RESULTS AND CONCLUSIONS: The ERDC trunnion-rod microcrack detection system is still in its development stage, and this Greenup Lock and Dam inspection trip was primarily intended to evaluate the robustness and field performance of the guided-wave methods being developed at the ERDC test bed. In general, good agreement was found between the data being collected on embedded laboratory rods at ERDC and the field data collected at Greenup Lock and Dam. Some differences in optimal setup were observed, such as the use of a diplexer pulsing one large element

was seen to perform better at ERDC, while a pitch-catch configuration using two half-sized elements without a diplexer performed better in the field. This observation, however, may have been contributable to the preamplifier saturation problem discussed in the previous section.

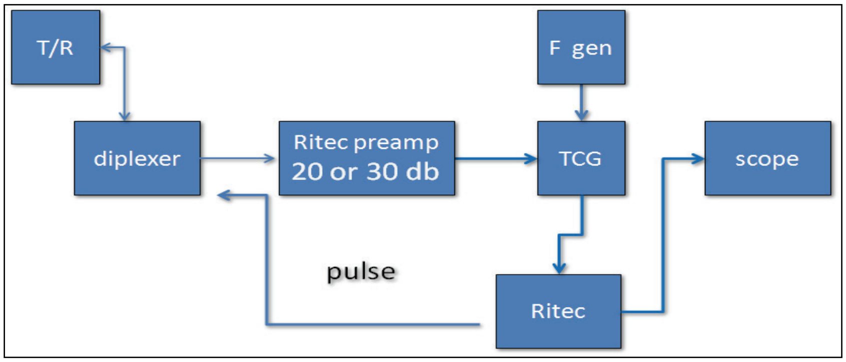

Figure 12. Block diagram of optimized system configuration.

The 200 rods at Greenup Lock and Dam were successfully tested, and a backwall signal was received for each one. These long-length and small-diameter rods presented a challenging high attenuation case for trunnion anchor rod testing. No defect echoes were detected in the observable parts of the signals. A small group of rods on the lower section of the east bank of pier 2 produced weak end-of-rod echoes. Retesting at a slightly higher frequency improved the amplitude of echoes from these rods, but only marginally. It is not known what created the effect, but the following theory is put forth: The rods may be contacting the containing sleeves to the point of causing a small degree of rod deflection and, hence, destructive guided-wave phase interference.

Significant improvements have already been made to the system and configuration used at Greenup Lock and Dam. Tentative plans are to return and re-inspect these rods with this new system configuration. The new transducer and gain circuits are expected to provide significantly stronger end-of-rod reflections while also allowing acquisition of data from the front section of the rod. This information was previously lost due to amplification-related issues discussed in this report. Additionally, improvements have also been made in finishing the rod ends so that better transducer coupling is assured.

This report also addresses the influence of rod diameter on guided wave attenuation, group velocity, and spectral mode spacings. Tension and length variations were also addressed, and a proposed methodology of robust time of arrival tracking was presented towards development of an in-place, active tension/defect monitoring system.

Ongoing research efforts will include the continued evaluation and development of non-linear guided-wave methods so that small microcracks still in the closed state can be detected in trunnion anchor rod testing. The progress documented here in the optimization and characterization of guided-wave propagation in damped rods is essential for the implementation of non-linear guide wave methods.

Appreciation is extended to Lockmaster Eric Dolly and others at Greenup Lock and Dam who provided outstanding support with this effort. Additionally, Tom Hood at Headquarters USACE

was key in the acquisition of a representative Greenup Lock and Dam post-tension rod for testing at the ERDC test bed.

ADDITIONAL INFORMATION: This CHETN is a product of the NavSys Program of the Navigation Safety Research Program being conducted at the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note may be addressed to James Evans: 601-634-2535; email: *james.a.evans@usace.army.mil*.

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